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Manned Spacecraft Center

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By Carlos S. Warren and Benny R. Baker
NASA Manned Spacecraft Center

SUMMARY

Measurements were taken during the MA-9 mission to establish the radiation received both inside and outside the spacecraft. The body dosage measured on the astronaut was measured by four film badges worn on the body and inside the helmet. Radiation levels within the spacecraft were measured by a nuclear emulsion pack placed behind the instrument panel and by an ionization chamber attached to the inside of the egress hatch cover. The exterior environment measurements were made by Geiger tubes mounted on the vehicle retrorocket package. Dose measurements on the film badges worn by the astronaut show that less than 12 to 14 milliroentgens, gamma equivalent body surface dose, were received from electrons and/or gamma rays. The exterior environment measurements recorded the decay of Starfish electrons to a level between 10 and 20 percent of the July 1962 value. This amount is considered safe at Mercury altitudes, even for extended missions.

INTRODUCTION

The ninth Mercury-Atlas mission (MA-9) was the second of the Mercury flights to intercept the South Atlantic geomagnetic anomaly, which is known to contain energetic protons and electrons of the Van Allen belt and electrons trapped as a result of the high-altitude nuclear test performed by the United States on July 9, 1962 (ref. 1). The electrons trapped as a result of the nuclear test were emitted by the radioactive decay of fission nuclei. Those having the proper pitch angles were subsequently trapped by the earth's geomagnetic field, executing oscillatory motion in latitude along magnetic lines and drifting eastward in longitude. Energies of the electrons are as high as 10 Mev (ref. 2).

Both the MA-9 astronaut and the spacecraft were instrumented with radiation detectors. The dose received by the astronaut was monitored with standard DuPont electron-gamma sensitive film placed on his inner right thigh, on his right and left chest, and inside his helmet. Radiation levels at other points in the spacecraft were monitored by a Model 866, 0- to 1-r Bendix ionization chamber mounted on the egress hatch and by a nuclear emulsion pack mounted behind the left instrument console. The film and nuclear emulsions were furnished and calibrated and their data were analyzed by Dr. H. J. Schaefer, U.S. Naval

School of Aviation Medicine, Pensacola, Florida. The emulsion and the ionization chamber were identical to those carried on the eighth Mercury-Atlas (MA-8) flight (ref. 3). The radiation environment exterior to the vehicle was monitored by two Geiger tubes mounted on the retrorocket package.

SYMBOLS

B, L	two-dimensional coordinates that give location in terms of the earth's magnetic field intensity B and a magnetic shell parameter L measured from the center of the earth to the intersection of the equatorial plane with the magnetic line of force through the point in question; B is measured in gauss, and L in earth radii.
dA_n	nth incremental area, cm^2
$\left(\frac{dE}{dx}\right)_i$	average linear energy transfer (LET) of protons in the i th grain-count class, Mev-cm^{-1}
F	total relative response of the Geiger counter, steradians
F_n	average relative response of the detector over the n th area, steradians
K	conversion factor of energy per mass to dose, 1.72×10^{-8} roentgens/ Mev-gm^{-1}
$N(E_p)$	flux of protons at energy E_p , protons/ $\text{cm}^2\text{-sec}$
r_n	distance between the Geiger tube and the n th area increment, cm
t	elapsed time from July 9, 1962, days
x_i	total proton track length in the emulsion volume in the i th grain-count class, cm
V	emulsion volume, cm^3
x, y, z	coordinate axes of the Geiger counter (fig. 12)
Z	charge number of an atom
θ	polar angle, deg
ρ	density of tissue, gm-cm^{-3}
φ	azimuthal angle, deg
Φ	electron flux, electrons/ $\text{cm}^2\text{-sec}$

Φ_0 initial Starfish electron flux, electrons/cm²-sec
 $\Phi(v)$ maximum detector response at voltage v, electrons/cm²-sec

EQUIPMENT

Radiation measurements on the MA-9 mission were made by film badges on the astronaut, nuclear emulsions behind the left instrument console, and an ionization chamber on the interior of the egress hatch. Particle flux outside the spacecraft was monitored by two Geiger counters.

The astronaut was instrumented with DuPont dosimeter film badges, type 545, at each of the following locations: no. 1, right loin; no. 2, right chest; no. 3, left chest; and no. 4, inside helmet.

The nuclear emulsion pack, which was cast in epoxy resin approximately the thickness of the space suit, was located behind the left instrument console (fig. 1). The pack contained eight 1- by 3-inch Ilford plates. Six of the plates were G-5 emulsions with a nominal thickness of 50 microns, one was a G-5 emulsion with a thickness of 100 microns, and one was a K-2 emulsion with a thickness of 50 microns. Since the manufacturing date of the emulsions was March 29, 1963, the emulsions were 47 days old when flown and 57 days old when developed.

The ionization chamber flown on the MA-9 spacecraft was the same type as that used on the MA-8 mission (ref. 3) and was located in approximately the same place, on the interior of the egress hatch (fig. 2). This location is behind the thinnest material on the spacecraft, approximately 0.6 gm/cm².

The particle flux encountered on the MA-9 mission during the passage through the South Atlantic magnetic field anomaly was monitored by Geiger tubes mounted on the spacecraft retrorocket package, as shown in figures 3 and 4. The tubes were Amprex 18529 with a stainless-steel wall thickness of approximately 0.09 gm/cm². One tube was collimated to view along the spacecraft roll axis, and the other viewed a hemispherical area at an angle of approximately 40° to the roll axis.

The tubes were sensitive to electrons greater than 0.25 Mev in energy and protons greater than 6 Mev. The uncollimated tube was fitted with a 1-mm tungsten shield to eliminate electrons with less than approximately 3 Mev in energy and protons with less than 27 Mev. The output of the detectors was put into a 0- to 3-volt voltage controlled oscillator. The noise level of the oscillator, 0.02 volt, corresponded to a Geiger tube output of 50 counts/sec. The proton geometric factor of the uncollimated tube was approximately 0.1 cm² and that of the collimated tube approximately 0.004 cm². A description of the Geiger tube package is presented in the appendix.

RESULTS AND DISCUSSION

Measurements Made Inside Spacecraft

Dose measured on the astronaut.- Films of the same emulsion and carton number as those carried by the astronaut were used as sea-level controls. At all times except during the flight, these films were kept in close proximity to the flown films. Another sea-level control group was kept at Pensacola, Florida, and a third control group was used to establish the density curve of the film by exposure to doses from 2 to 500 milliroentgens of radium-gamma radiation obtained from a 15-millicurie radium source.

The flown films showed densities slightly higher than the sea-level controls and slightly lower than the test film exposed to a gamma dose of 19.5 milliroentgens. The density values involved lie close together on the initial part of the density curve where the gradient is small; however, they allow a dose determination with an estimated error of 20 to 30 percent. The following table is typical of the densities involved:

Exposure	Mean absolute density
Flown film no. 3 (astronaut's left chest)	0.212
Control, exposed to 19.5 milliroentgens gamma radiation	.232
Sea-level control, unexposed	.168

Interpolation on the density curve shown in figure 5 led to an equivalent gamma dose of 13.4 milliroentgens for film no. 3. Similar density measurements revealed doses of 14 milliroentgens for no. 1, 13 milliroentgens for no. 2, and 12 milliroentgens for no. 4. However, a microscopic comparison of the gamma-irradiated and flown films showed different grain patterns. Figures 6 and 7 demonstrate these different patterns in detail. Figure 6 shows the grain pattern of the gamma-exposed emulsion, and figure 7 presents randomly selected visual fields of film no. 3. The streakiness of the grain pattern in the flown emulsion was very pronounced. Of special interest was the heavy streak in the left microgram of figure 7 which was apparently produced by a heavy nucleus of high Z number.

The marked difference of the grain structures indicated that the film exposure was not entirely due to electrons and/or gammas, but was also due to protons or other heavily ionizing particles. This conclusion was borne out by the data from the Ilford G-5 nuclear emulsions located on the vehicle instrument console, which are discussed subsequently. The conclusion to be drawn from the combined densitometric and microphotographic evaluation of the film badges is that the dose from electrons and/or gamma rays to the astronaut was less than 12 to 14 milliroentgens.

Nuclear emulsion data.- Postflight microscopic inspection of the processed plates from the nuclear emulsion pack revealed that proton tracks constituted by far the largest part of the exposure. Figure 8 shows a typical field of a G-5 emulsion (50-micron nominal thickness) that was flown. The proton tracks are pronounced on the low background.

The proton dose on the emulsion was determined by using a quadratic reticule in the eyepiece of the microscope to scan a defined area of the emulsion. The lengths and grain densities of all tracks in the area were evaluated. The total emulsion volume, in which all tracks were analyzed, was determined by using the measured value of 62 microns for the unprocessed emulsion thickness. If this total emulsion volume is visualized as being replaced by tissue, the equivalent total ionization which the same proton population would have produced can be determined. A basic difficulty of the grain-counting method rests in the fact that toward higher grain densities, the grain count becomes inaccurate and finally impossible. A lower energy-resolution limit of approximately 36 Mev was established for the emulsion used. It is possible, however, to determine a data point at approximately zero energy by counting the number of tracks that terminate in the emulsion volume. Therefore, the differential energy flux can be directly measured at near 0 Mev and above 36 Mev, leaving only the 0 to 36 Mev region to be interpolated. The interpolation was carried out by distributing the tracks that fall in the high-grain-count class in such a way that a smooth joining of the differential spectrum was made between 0 and 36 Mev and the integral of the spectrum over that energy range resulted in the number of tracks counted in that region. Figure 9 shows the differential proton spectrum measured on the MA-9 mission (ref. 4). The plotted points are the mid-points of the selected energy intervals (see table I).

The tissue dose was determined by regarding the emulsion volume as being replaced with tissue and by calculating the energy deposited per gram by the protons passing through the emulsion, that is, in roentgens

$$\text{Dose} = K \sum_i \left(\frac{dE}{dx} \right)_i x_i \frac{1}{\rho V} \frac{1}{2.33} \quad (1)$$

where 2.33 is the ratio of emulsion $\frac{dE}{dx}$ to that of tissue. The $\frac{dE}{dx}$ values used are an average of those presented in reference 5 for Ilford G-5 emulsions. Table I summarizes the information derived from a typical volume of emulsion. The measured gamma equivalent tissue dose, corrected for background, was 26.9 milliroentgens.

The proton-track population in the MA-9 plates showed a strong directional effect. The method of assessing the dose was not influenced by this directional effect since the actual total number of protons and their total ionization in the scanned emulsion volume was determined, and no assumptions on the solid angle of incidence entered the computation.

To estimate qualitatively the electron population in the spacecraft, the nuclear emulsions were examined for evidence of electrons. This procedure was

somewhat difficult because of the many proton tracks in the flown plates. However, by selecting partial areas which were relatively free of proton tracks and comparing them with areas of equal size in the sea-level control plates, it was determined that the number of electrons in the flown and sea-level control plates was not significantly different.

Ionization chamber measurements.- The ionization chamber was placed on the egress hatch cover within 1 hour after lift-off of the MA-9 spacecraft and remained there until just prior to retrofire (approximately 33 hours). Upon recovery, the meter indicated a total exposure of 170 milliroentgens.

Calibration of the ionization chamber to a Co^{60} gamma-ray source established that the detector reading was low by an average of 6.9 percent with a standard deviation of 3.0 percent. It is estimated that a reading error of ± 10 milliroentgens could have been made. Taking into account the low detector response and possible reading error, the true reading should have been a gamma equivalent dose of

$$(1.069 \pm 0.030)(170 \pm 10 \text{ milliroentgens}) = 182 \pm 12 \text{ milliroentgens} \quad (2)$$

The MA-9 dose recorded by the ion chamber was approximately three times that recorded on the MA-8 mission, which was consistent with the relative lengths of time spent in the anomaly region.

Exterior Environment Measurements

Two Geiger tubes, mounted on the exterior of the spacecraft retrorocket package, monitored the particle flux during passage through the South Atlantic magnetic field anomaly. Calibrations performed with a 3-Mev Van de Graaff generator showed that the uncollimated-tube noise level of 0.02 volt corresponded to a lower detection-level limit of approximately 2×10^4 electrons/cm²-sec. Assuming 100-percent efficiency in the detection of the protons that penetrate the tube shielding and walls, the noise level combined with the geometric factor produced a proton detection limit of approximately 500 protons/cm²-sec.

The limit of 0.02 volt was never exceeded by the shielded tube during orbital passes through the anomaly; consequently, the flux of electrons greater than 3 Mev was less than 2×10^4 /cm²-sec and that of protons greater than 27 Mev was less than 500/cm²-sec.

Data were gathered by the collimated detector on two passes through the anomaly; the first was the portion of the seventh orbital pass between the geographic coordinates of 30.7° S. latitude, 29° W. longitude, and 31° S. latitude, 1° E. longitude, and the second was the portion of the eighth orbital pass between 32° S. latitude, 26° W. longitude, and 30° S. latitude, 15° W. longitude. Altitude varied between 263 and 250 km on the seventh orbital pass,

and between 256 and 250 km on the eighth orbital pass. When transformed to the B and L coordinates of reference 6 where L is the magnetic shell parameter in earth radii, and B is the magnetic field intensity in gauss, B varied between 0.2223 and 0.2532 on the seventh orbital pass and between 0.2334 and 0.2454 on the eighth orbital pass. The value of L varied between 1.268 and 1.540 on the seventh orbital pass and between 1.376 and 1.427 on the eighth orbital pass.

The lower proton detection limit of the collimated tube was calculated to be approximately 10^4 protons/cm²-sec. This value is several orders of magnitude higher than any proton flux measured at these B and L values and, therefore, it is concluded that the counts recorded were entirely from electrons.

The mouth of the collimator for the detector was rectangular with dimensions of $\frac{13}{16}$ inch by $1\frac{15}{16}$ inches. The collimator profile was mapped at several azimuthal angles with respect to the collimator center which produced relative angular response with respect to the tube normal at the center of the collimator. Figure 10 shows the relative tube and collimator response along the long and short axes.

The response of the collimated detector over its subtended solid angle relative to the response at the normal angle of particle incidence (maximum response) was obtained by dividing the collimator area into n increments dA_n and multiplying the solid angle subtended by dA_n by the average relative response over that area; that is, if F_n represents the relative response over the n th area,

$$F = \sum_n F_n \frac{dA_n}{r_n^2} = 9.94 (10^{-2}) \text{ steradians} \quad (3)$$

where F is the relative response of the detector, and r_n is the distance from the tube center to the center of dA_n .

The maximum response of the detector was measured at several electron energies and normalized to the presumed Starfish electron spectrum furnished by Dr. W. N. Hess of NASA Goddard Space Flight Center and shown in figure 11.

Figure 12 shows the normalized maximum response in electrons/cm²-sec as a function of detector output voltage. If $\Phi(v)$ is the maximum response in electrons/cm²-sec at some voltage v , then the omnidirectional response is

$$\Phi = \frac{4\pi\Phi(v)}{F} \text{ e/cm}^2\text{-sec} \quad (4)$$

Table II lists Φ measured on the MA-9 mission as a function of B and L.

Figure 13 shows the measured electron flux in the anomaly as a function of L. Also shown are the calculated fluxes for the same B and L based on July 1962 Starfish electron data obtained from Dr. Hess. The decay of the belt was evident over the 311-day period between the belt formation and the time of the MA-9 mission. The data show the belt strength to be between 10 and 20 percent of its initial value by the time of the MA-9 flight (May 15, 1963). These data compare favorably with the decay data of reference 7 in which radio measurements were made in Peru of synchrotron radiation at 30 and 50 megacycles per second. The synchrotron measurements established a decay curve of

$$\Phi = \Phi_0 \frac{1}{1 + t/60} \quad (5)$$

where Φ_0 is the initial belt value and t is elapsed time in days. For a t of 311 days, equation (5) gives

$$\Phi = 0.16 \Phi_0 \quad (6)$$

CONCLUSIONS

Dose measurements on the MA-9 pilot using film badges established that the astronaut received less than 12 to 14 milliroentgens, gamma equivalent body surface dose, from electrons and/or gamma rays.

Dose measurements inside the vehicle using nuclear emulsions located behind the left instrument console and an ionization chamber attached to the egress-hatch-cover interior established the following:

- (1) A proton dose of 27 milliroentgens was measured by the emulsions.
- (2) The protons were generally below 100 Mev in energy, and showed a strong directionality, presumably due to local absorbing matter around the emulsions.
- (3) Electron background in the emulsions was not significantly different from sea-level controls, again presumably due to local absorbing matter.
- (4) The ionization chamber measured 182 ± 12 milliroentgens, gamma equivalent dose, in the most exposed portion of the vehicle. The wall thickness of the chamber corresponded to a tissue depth of 0.2 to 0.4 gm/cm².

Electron flux measurements established that the Starfish belt had decayed to between 10 and 20 percent of its July 1962 value at the time of the MA-9 flight. The Starfish electrons present no hazard at Mercury altitudes, even for relatively extended missions.

Manned Spacecraft Center

National Aeronautics and Space Administration

Houston, Texas, October 15, 1964

APPENDIX

THE MA-9 ELECTRON FLUX DETECTOR

The MA-9 electron flux detector was developed to convert the number of particles entering the Geiger tube into corresponding analog voltage. The analog voltage in turn varied the frequency of a voltage control oscillator (VCO). These frequency variations were recorded on magnetic tape carried on-board the MA-9 vehicle. The spacecraft location in orbit and the frequency variations provided the required data for determining the electron flux at a given location.

The instrument was constructed in two units: The first contained the Geiger tubes, monostable multivibrator, and the Eccles-Jordan flip-flop circuit, and was housed in a mounting attached to the outside of the spacecraft retro-rocket package. The second was the integrator circuit housed in a module mounted inside the retrorocket package. This inside location provided a more stable temperature than the outside surface.

The instrument was designed with two independent data channels. Figure 14 shows a block diagram of the complete instrument and figure 15 is a schematic diagram of one data channel, the high voltage d-c to d-c converter, and the voltage regulator.

The power for the Geiger tube was applied to the collector electrode through two load resistors. The portion of the signal which was developed across the smaller resistor was used to trigger the monostable multivibrator. The monostable multivibrator was composed of Q_1 , Q_2 , and the associated components. The resistor R_T and capacitor C_T were selected for a desired pulse width of approximately 7 μ sec. The pulse from the monostable multivibrator was used to trigger a flip-flop circuit (Q_3 and Q_4). The output of the flip-flop circuit was impressed across two resistors, one of which controlled the number of pulses required for maximum analog voltage output. The maximum acceptance voltage of the VCO was 3 volts.

The integrator received the pulses from the range adjustment, differentiated, clipped the negative portion, and used the positive portion to charge the integrating capacitor, C_1 .

The integrating circuit, which had a time constant of 11 seconds, converted the number of pulses into corresponding d-c levels.

The detector collimator was defined by a series of tungsten baffles. The high-density baffles presented a small surface for electron scattering inside the collimator and allowed the maximum collimation of the particles.

The data obtained on MA-9 were continuous over the period of operation. Preliminary data reduction was performed, and a readout of voltage at

half-second intervals was obtained. For ease of presentation, the half-second data were averaged over 10-second intervals by using an IBM 7090 program. These data are presented in table II and are plotted in figure 13.

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TABLE I.- RESULTS FROM EMULSION USED ON MA-9 MISSION

Grains per 100 microns	Proton mean kinetic energy, Mev	Tissue dose, milliroentgens	
		Flight emulsion	Sea-level control
< 48	360	0.99	0.35
48-73	153	2.09	.26
73-96	91	2.03	.18
96-120	62	2.39	.11
120-144	44	2.29	.10
> 144	18	<u>19.0</u>	<u>.92</u>
		28.8	1.92

TABLE II.- MA-9 ELECTRON FLUXES

B, gauss	L, earth radii	Φ , electrons/cm ² -sec	B, gauss	L, earth radii	Φ , electrons/cm ² -sec
0.22231	1.268	1.26×10^6	0.24133	1.4131	2.81×10^5
.22231	1.277	1.39×10^6	.24230	1.4165	2.59×10^5
.22386	1.277	1.48×10^6	.24338	1.4202	2.43×10^5
.22386	1.293	1.52×10^6	.24437	1.4236	2.25×10^5
.22464	1.299	1.53×10^6	.24540	1.4270	2.02×10^5
.22655	1.316	1.53×10^6	.23777	1.416	6.03×10^5
.22560	1.310	1.50×10^6	.23896	1.425	5.37×10^5
.22660	1.320	1.48×10^6	.24017	1.433	4.80×10^5
.22660	1.320	1.44×10^6	.24024	1.439	4.30×10^5
.22660	1.320	1.38×10^6	.24157	1.442	3.86×10^5
.22847	1.334	1.33×10^6	.24407	1.461	3.45×10^5
.22859	1.338	1.26×10^6	.24278	1.457	3.16×10^5
.22977	1.350	1.19×10^6	.24533	1.470	2.97×10^5
.23071	1.357	1.14×10^6	.24661	1.480	2.91×10^5
.23071	1.357	1.09×10^6	.24789	1.490	2.78×10^5
.23303	1.378	1.04×10^6	.24918	1.500	2.74×10^5
.23405	1.386	9.73×10^5	.24919	1.501	2.68×10^5
.23405	1.386	9.10×10^5	.25048	1.521	2.63×10^5
.23536	1.399	8.60×10^5	.25194	1.531	2.58×10^5
.23544	1.399	7.90×10^5	.25194	1.531	2.34×10^5
.23659	1.407	7.28×10^5	.25322	1.540	2.11×10^5
.23659	1.407	6.70×10^5	.2334	1.3765	4.70×10^5
.23740	1.3980	4.32×10^5	.2347	1.384	4.99×10^5
.23808	1.4007	4.10×10^5	.23558	1.3885	4.93×10^5
.23880	1.4037	3.77×10^5	.23624	1.3917	4.74×10^5
.23960	1.4067	3.39×10^5	.23685	1.3950	4.46×10^5
.24043	1.4098	3.10×10^5			

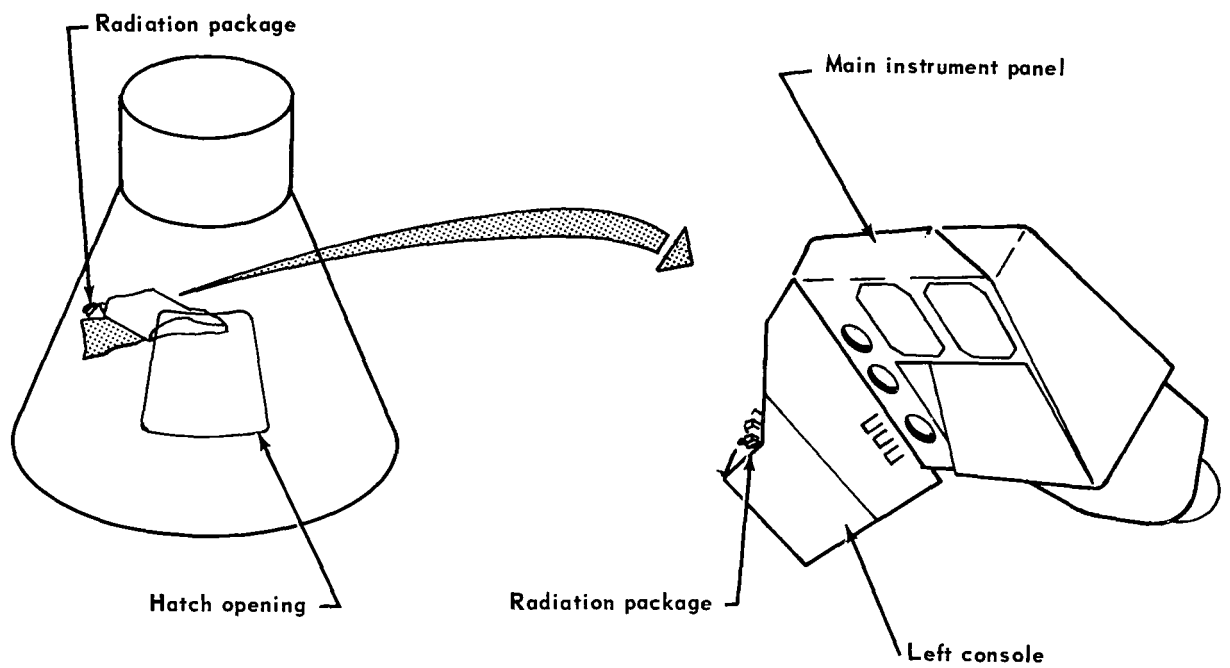


Figure 1.- Emulsion placement on instrument console.

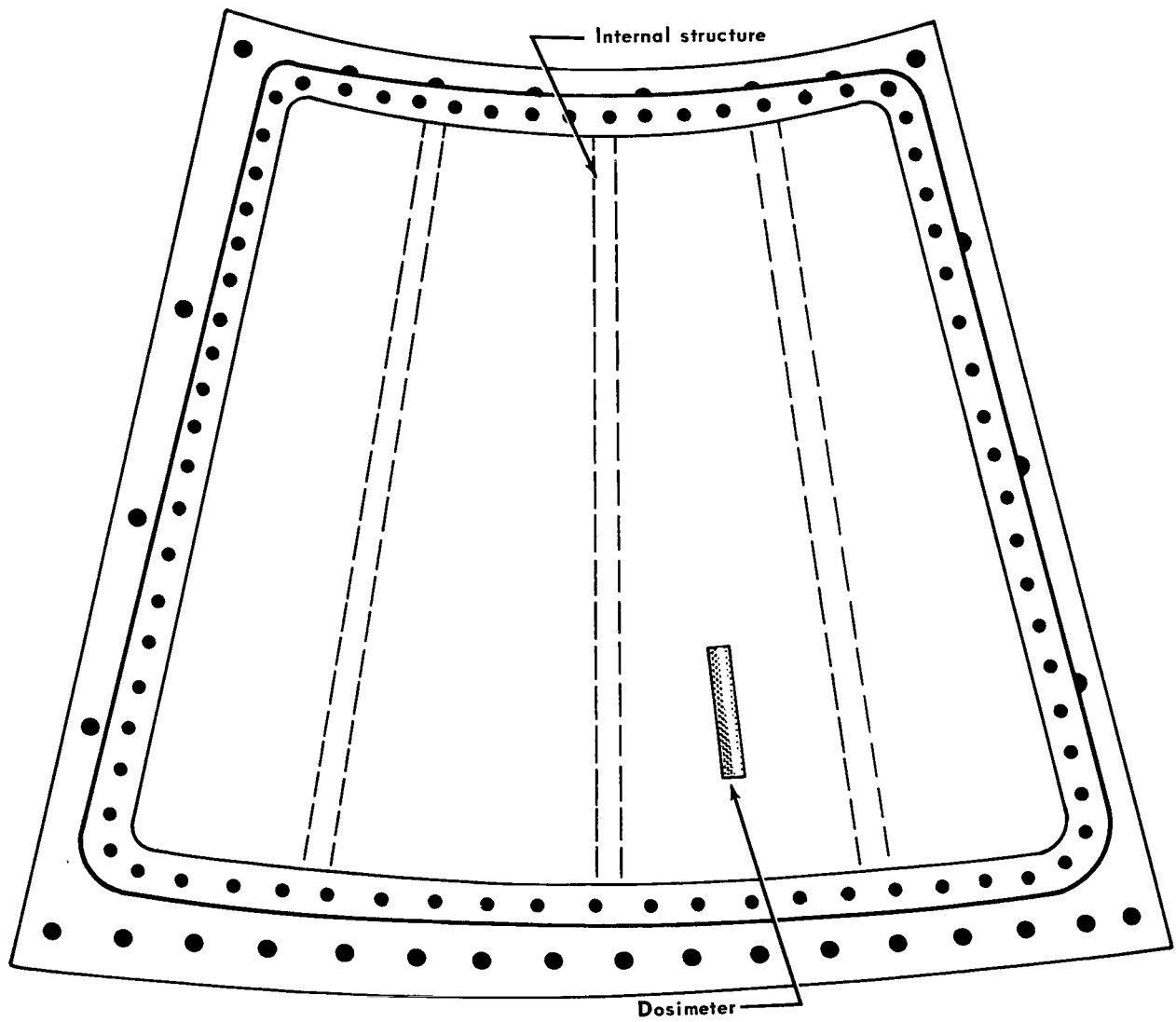


Figure 2.- Ion chamber position on the egress hatch cover.

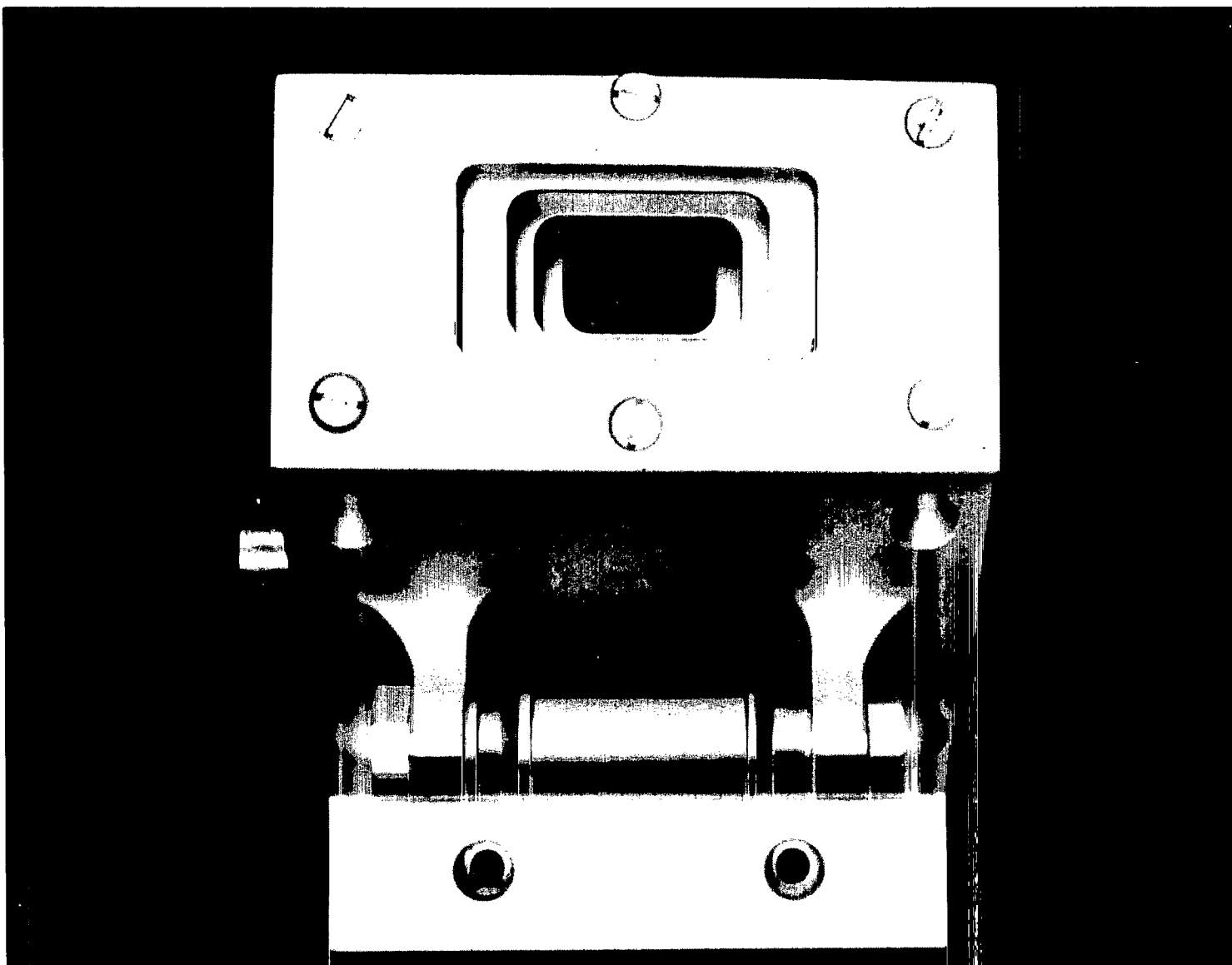


Figure 3.- MA-9 exterior environment detector.

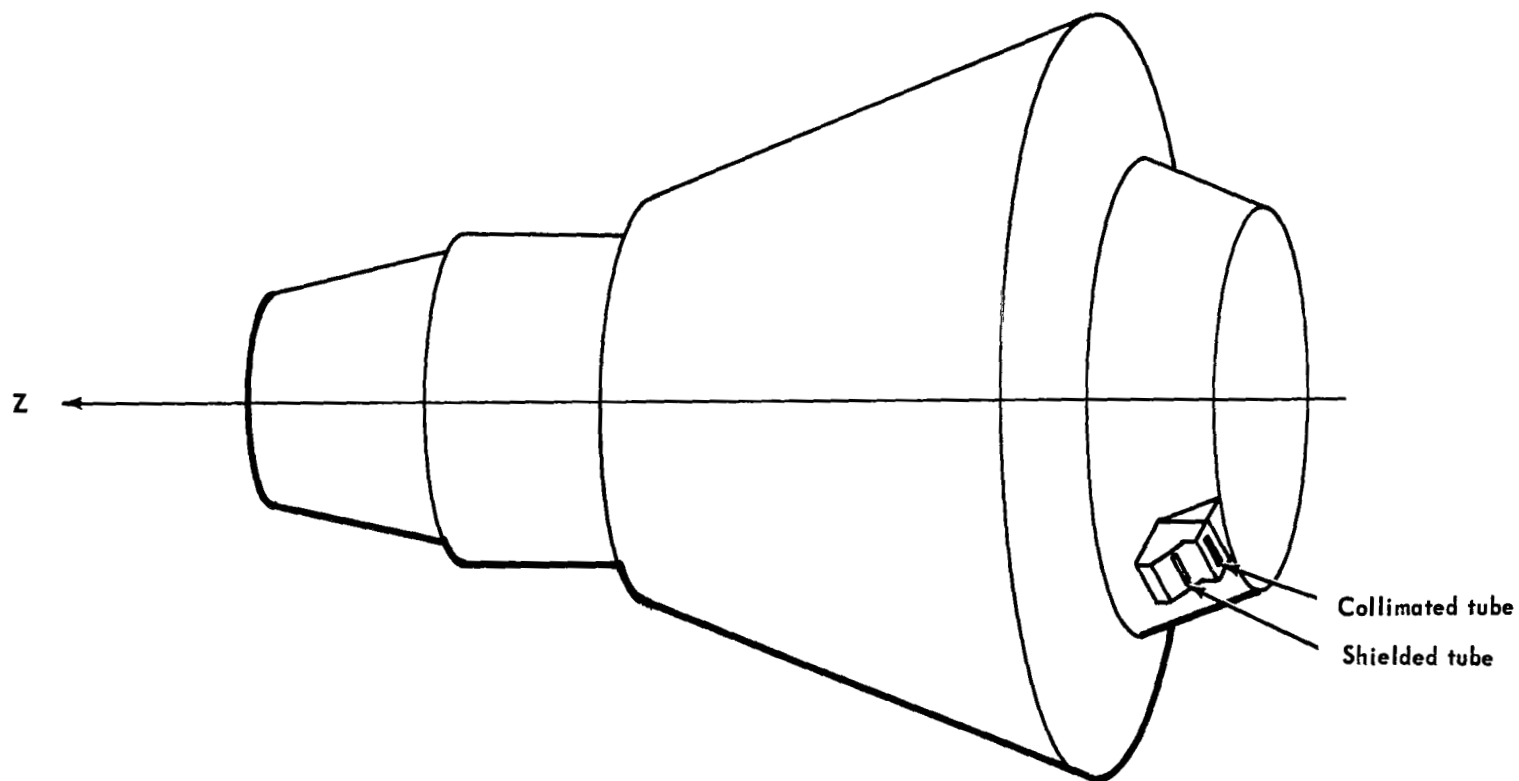


Figure 4.- Geiger tube placement.

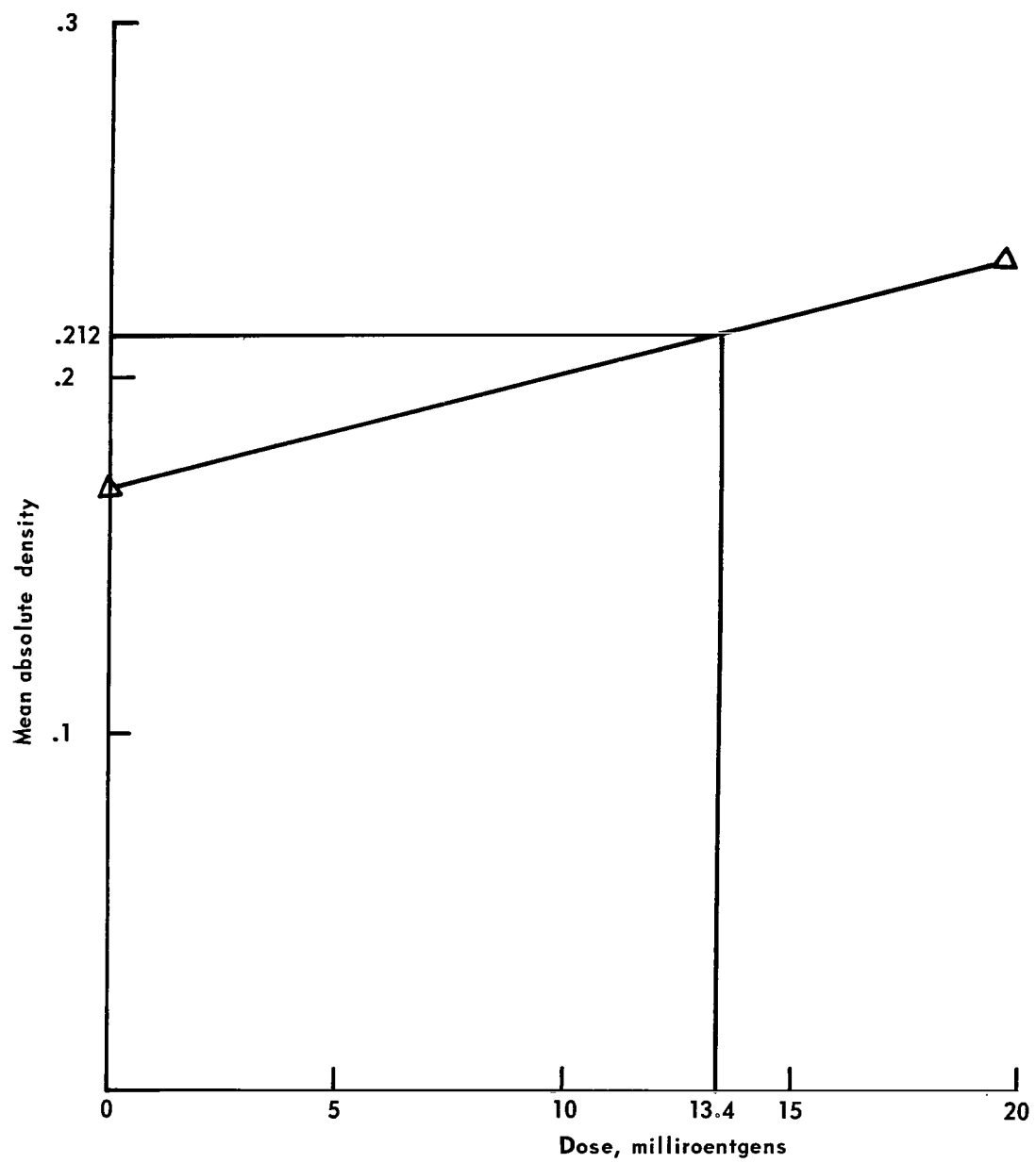


Figure 5.- Density curve for film no. 3 (astronaut's left chest).

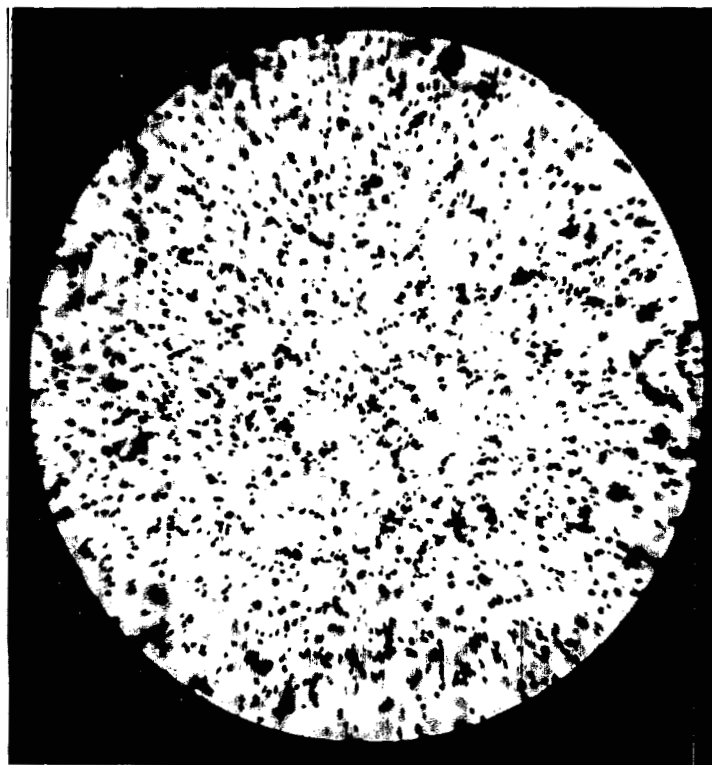
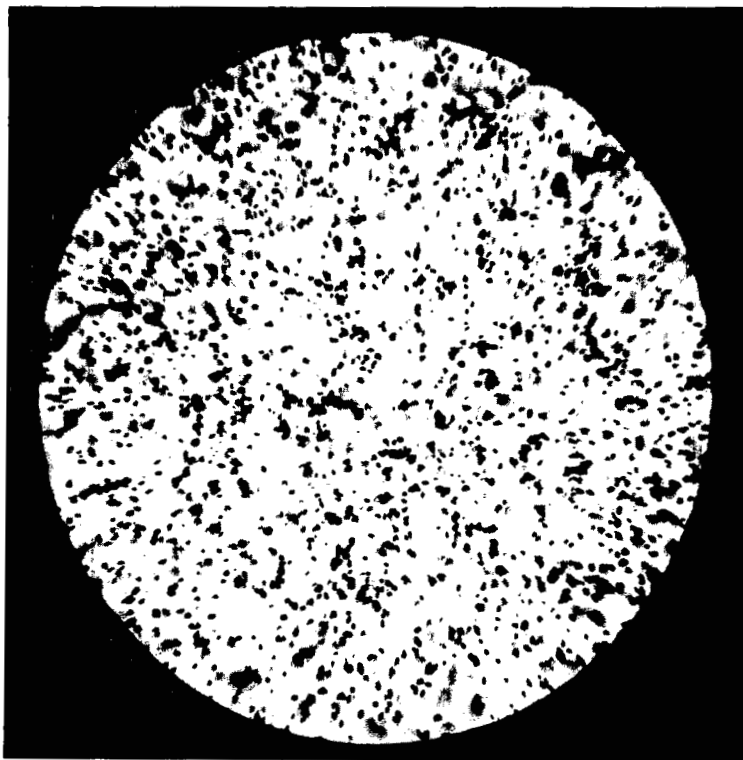


Figure 6.- Micrograms of DuPont dosimeter film type 545, exposed to 19.5 milliroentgens of radium-gamma radiation. Diameter of visual field: 345 microns.

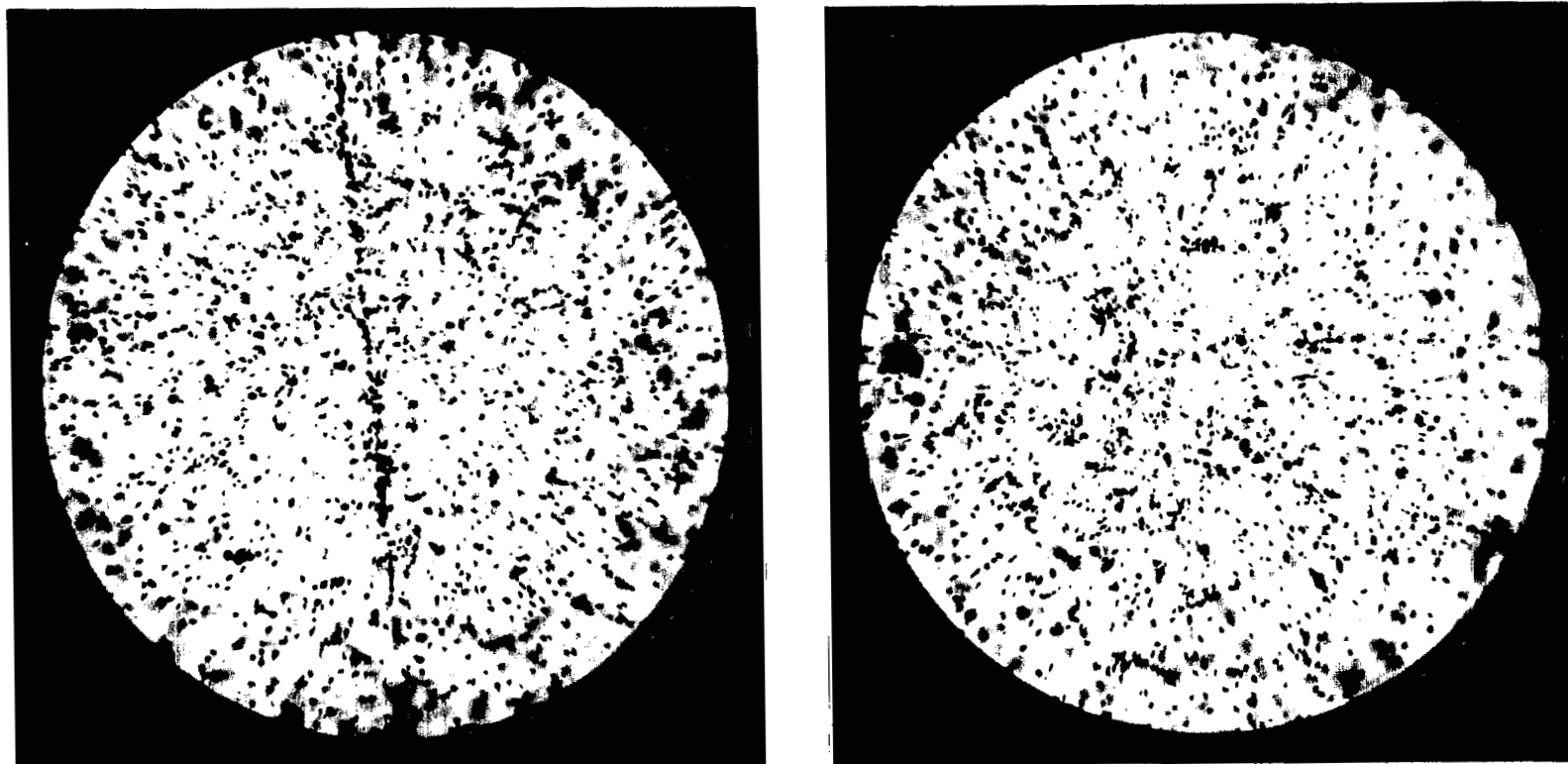


Figure 7.- Micrograms of DuPont dosimeter film type 545 carried by astronaut on left chest.
Diameter of visual field: 345 microns.

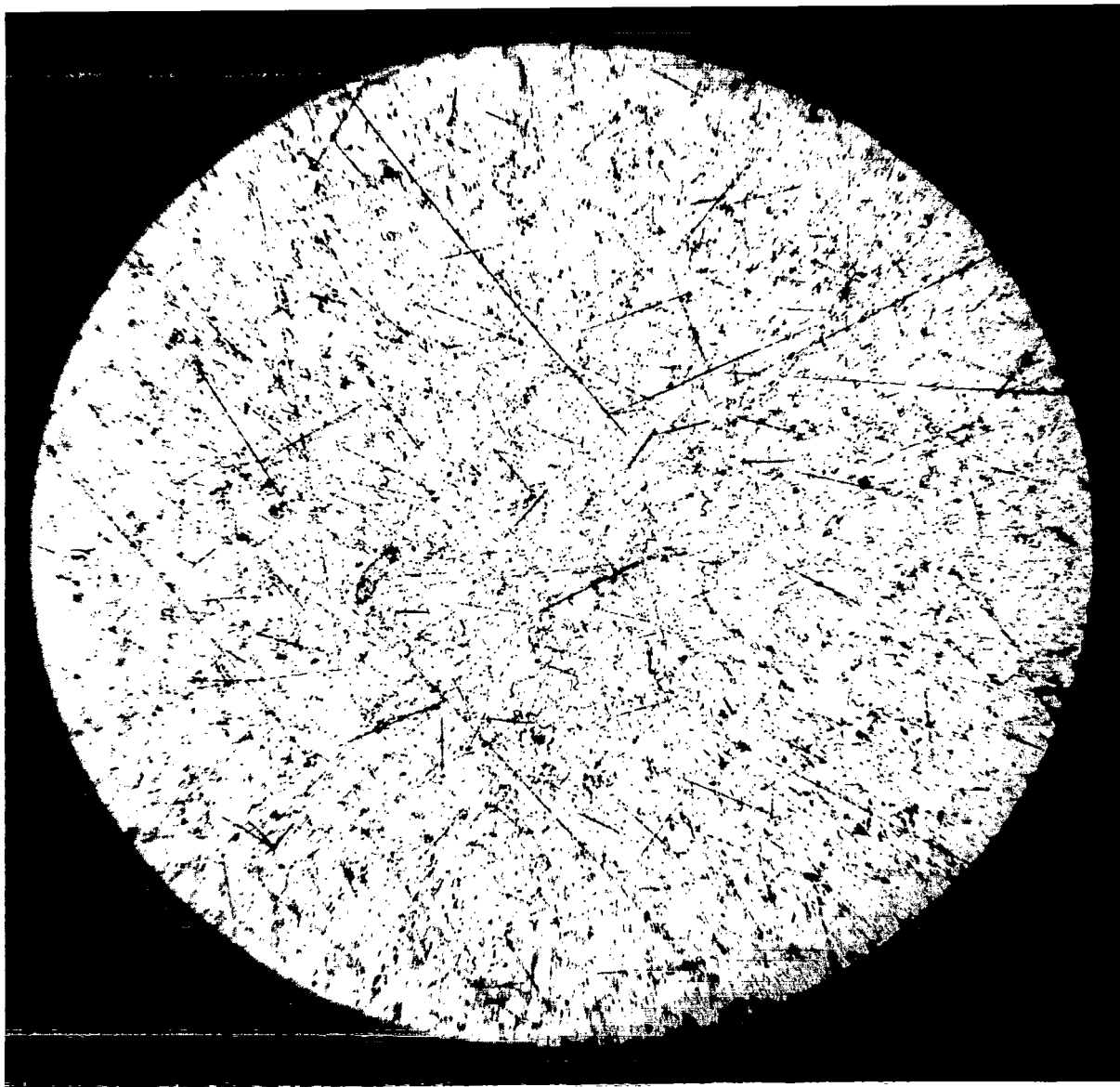


Figure 8.- Microgram of Ilford G-5 emulsion (50-micron nominal thickness) flown on MA-9 mission. Diameter of visual field: 735 microns.

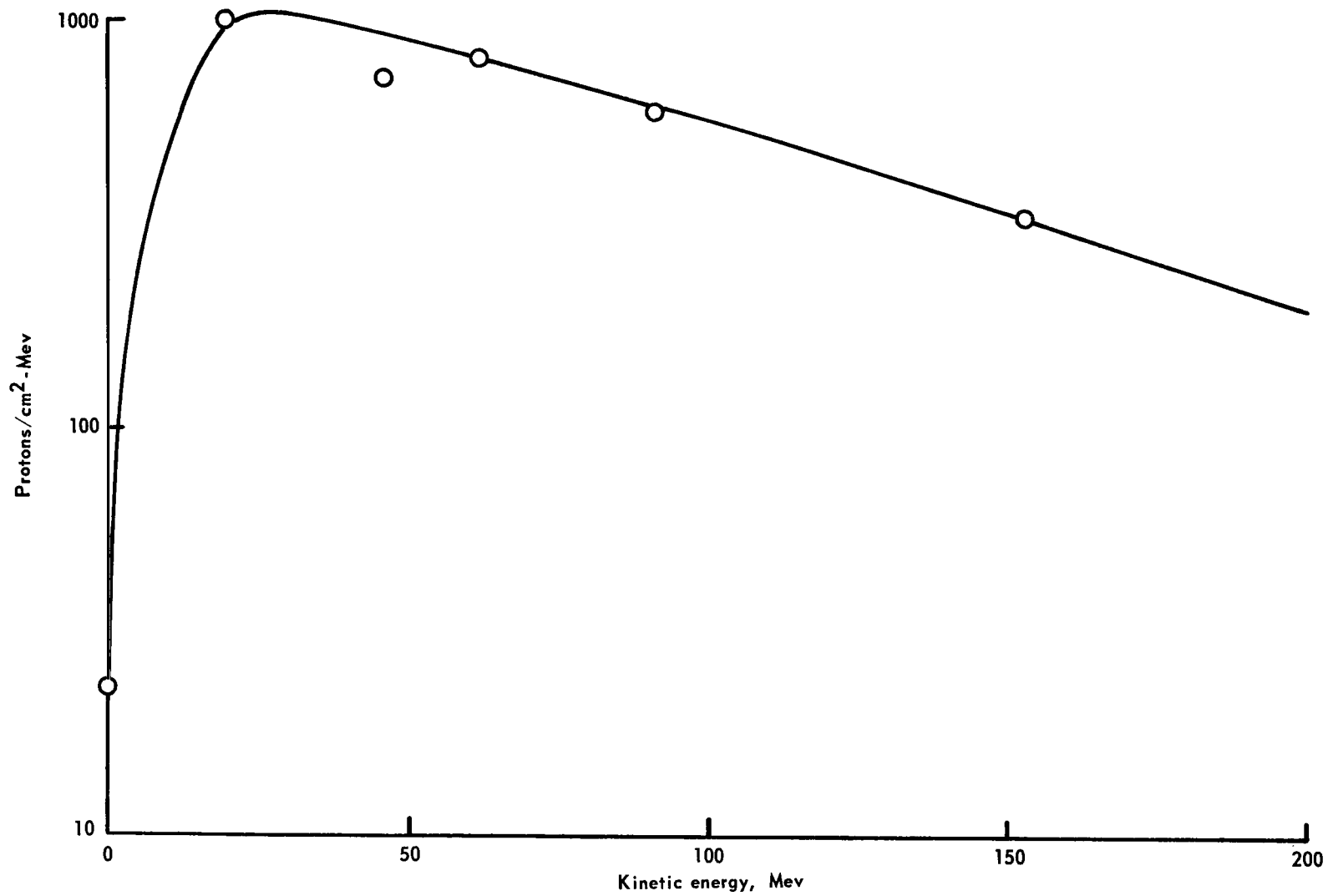


Figure 9.- MA-9 differential proton spectrum.

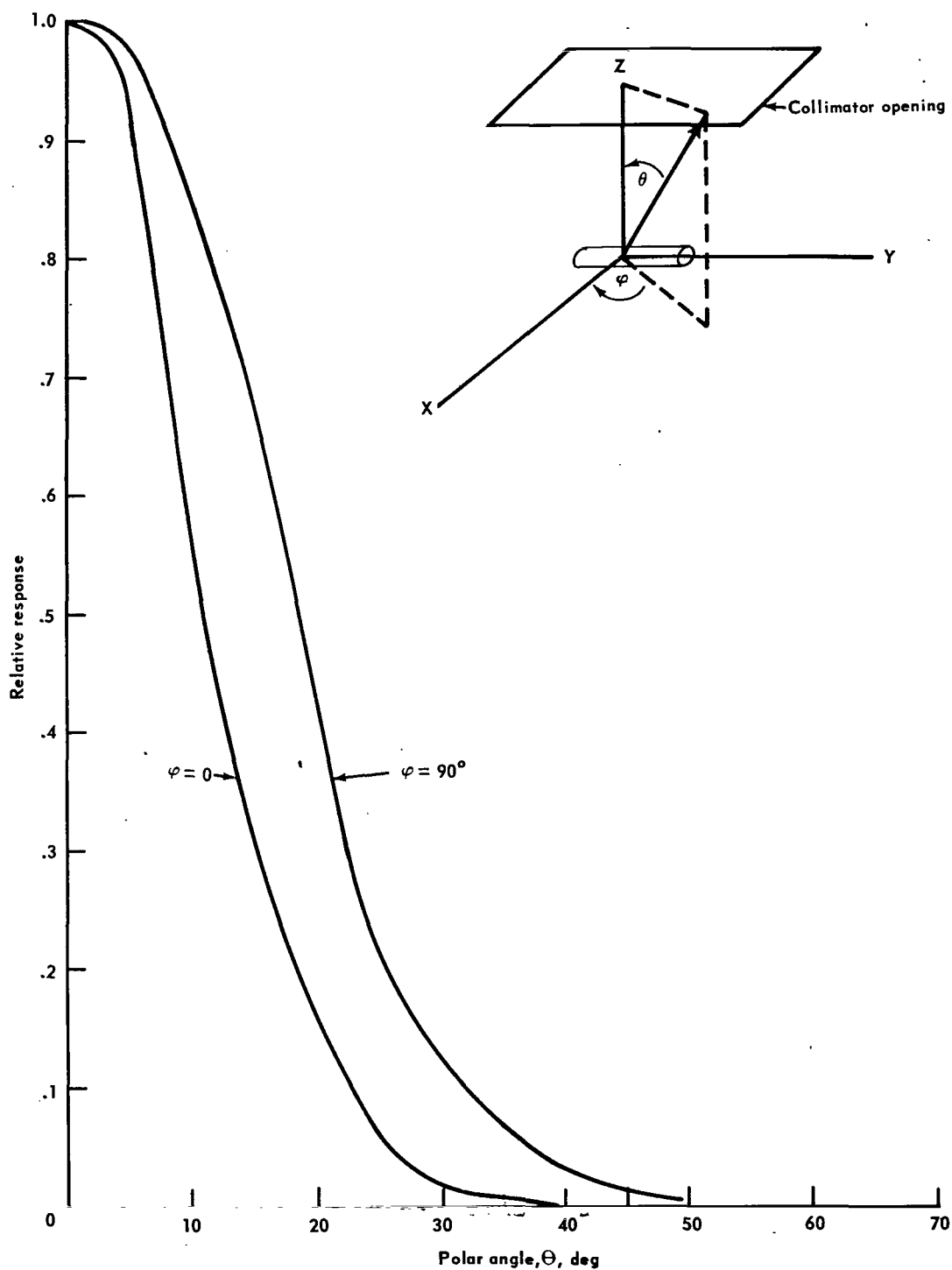


Figure 10.- Collimator effect on tube response.

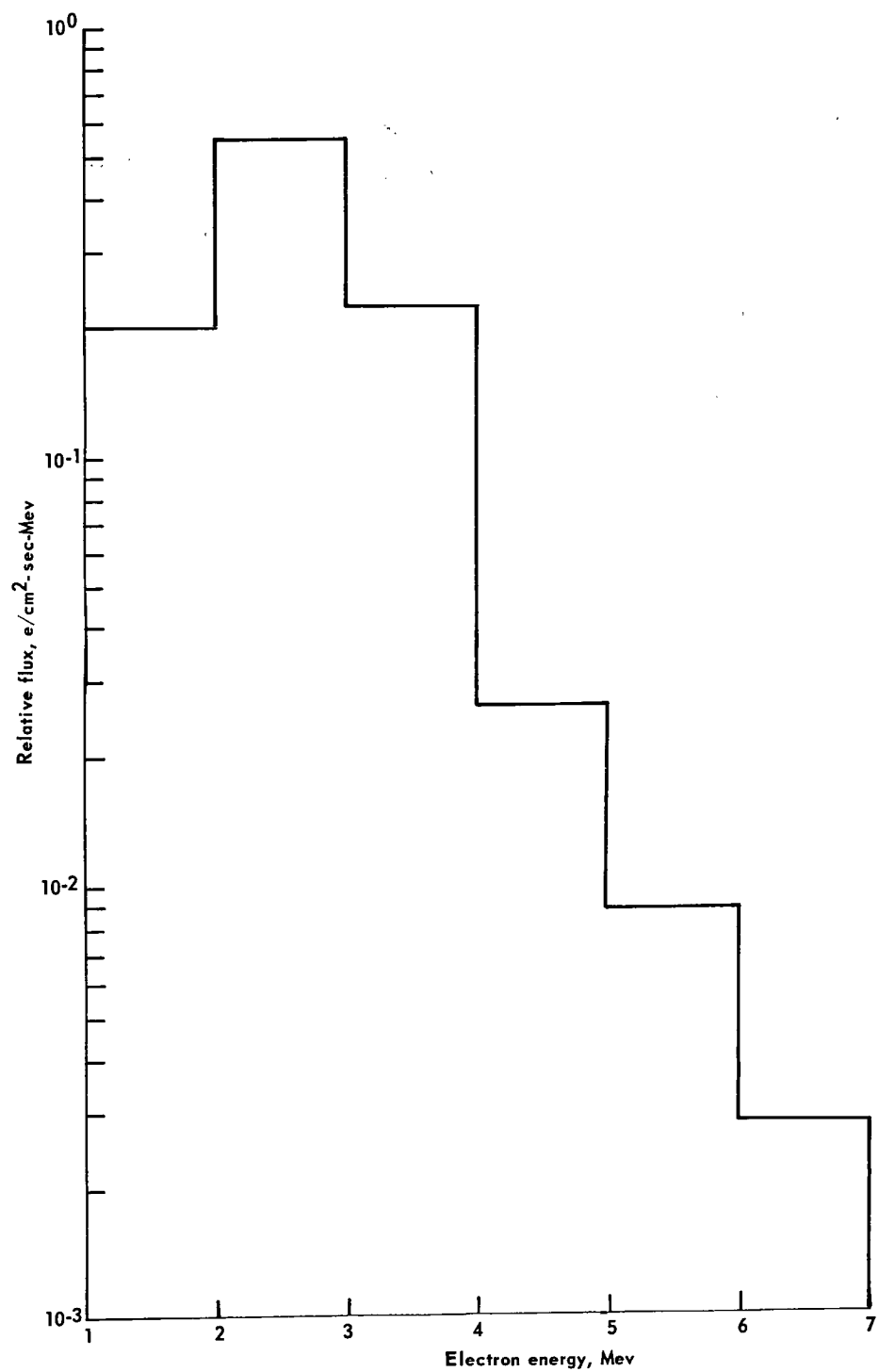


Figure 11.- Assumed Starfish electron spectrum at an altitude of 300 km, May 15 and 16, 1963.

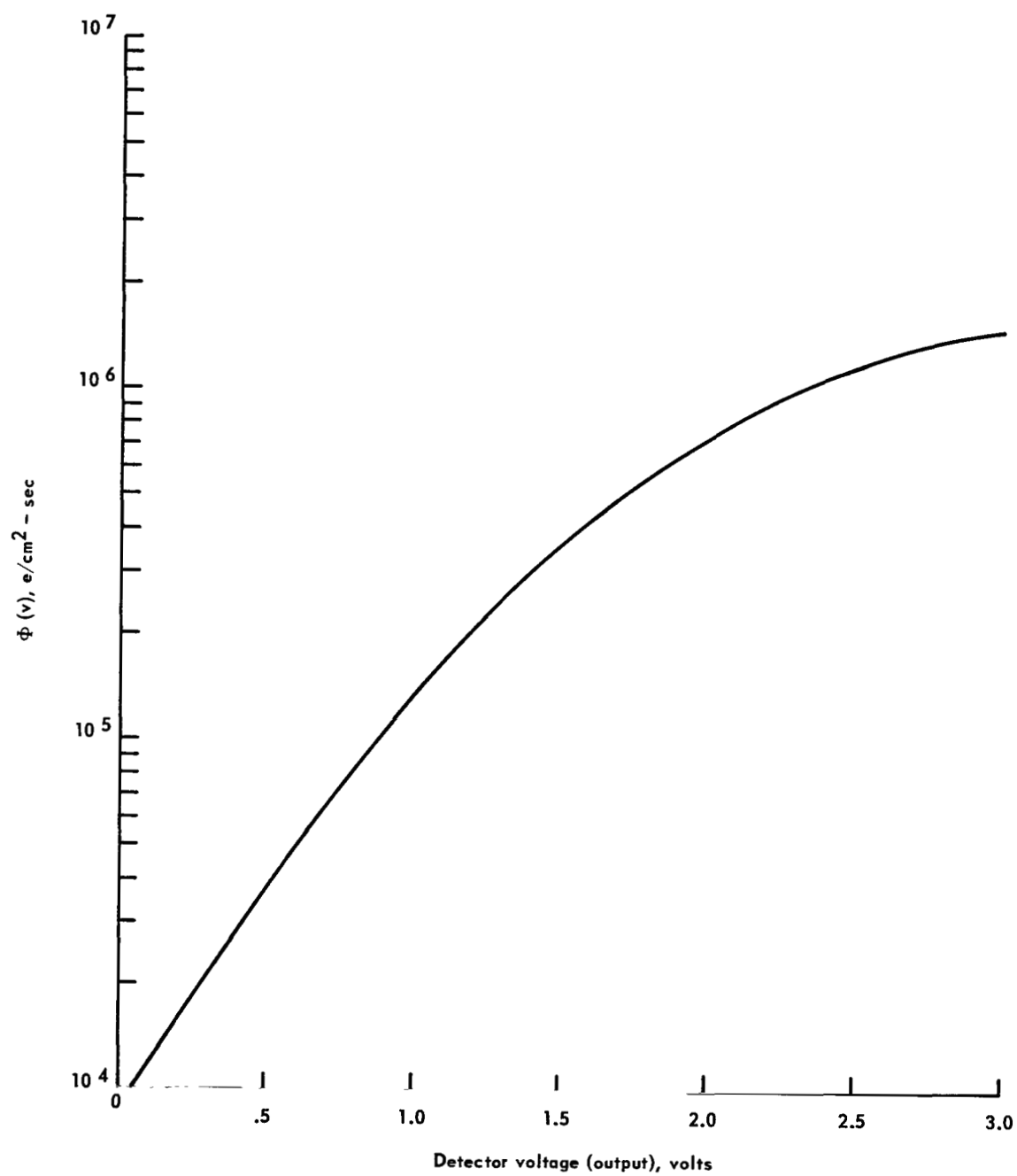


Figure 12.- Maximum detector response.

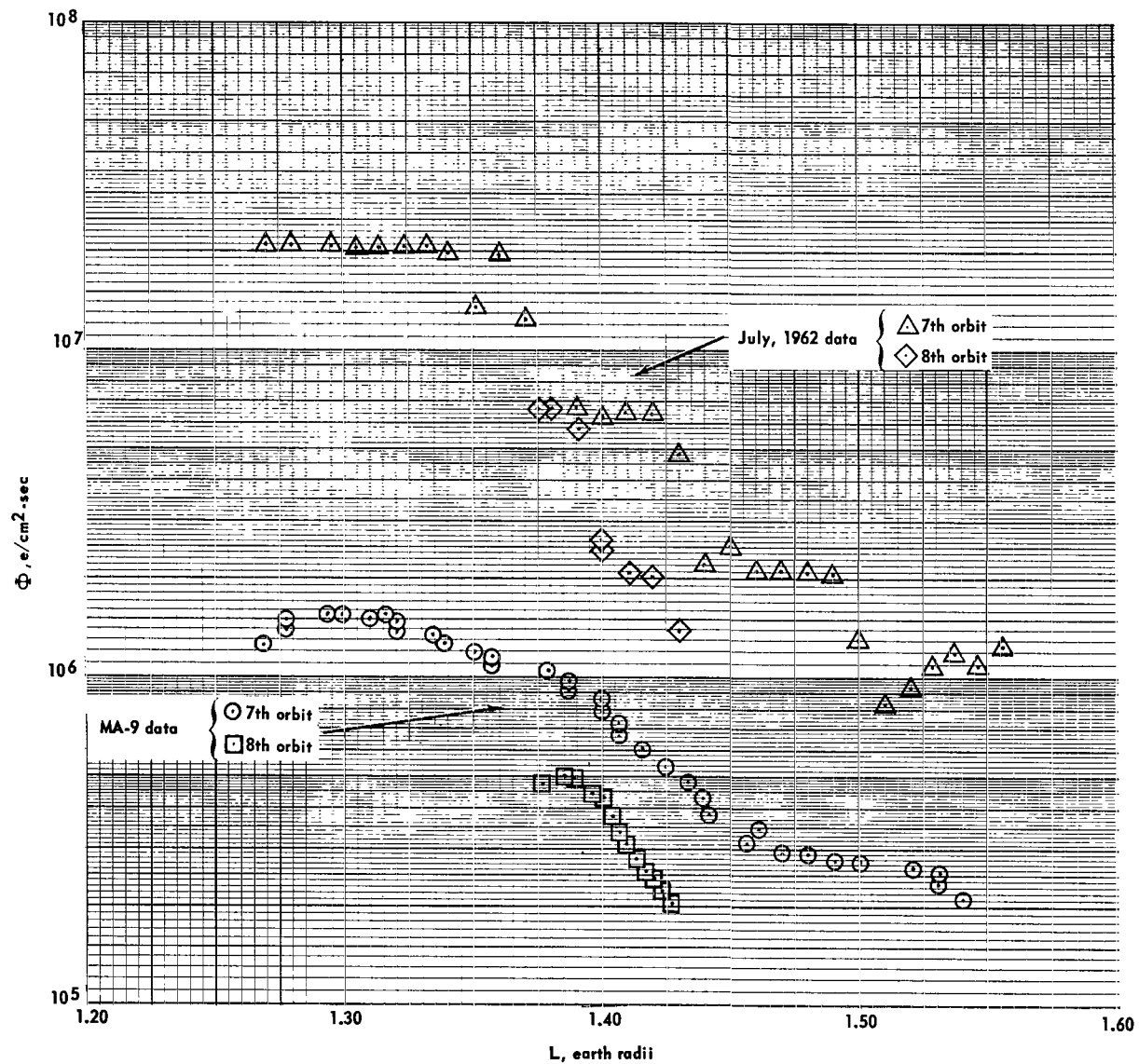


Figure 13.- Electrons in the anomaly, $E > 0.25$ Mev.

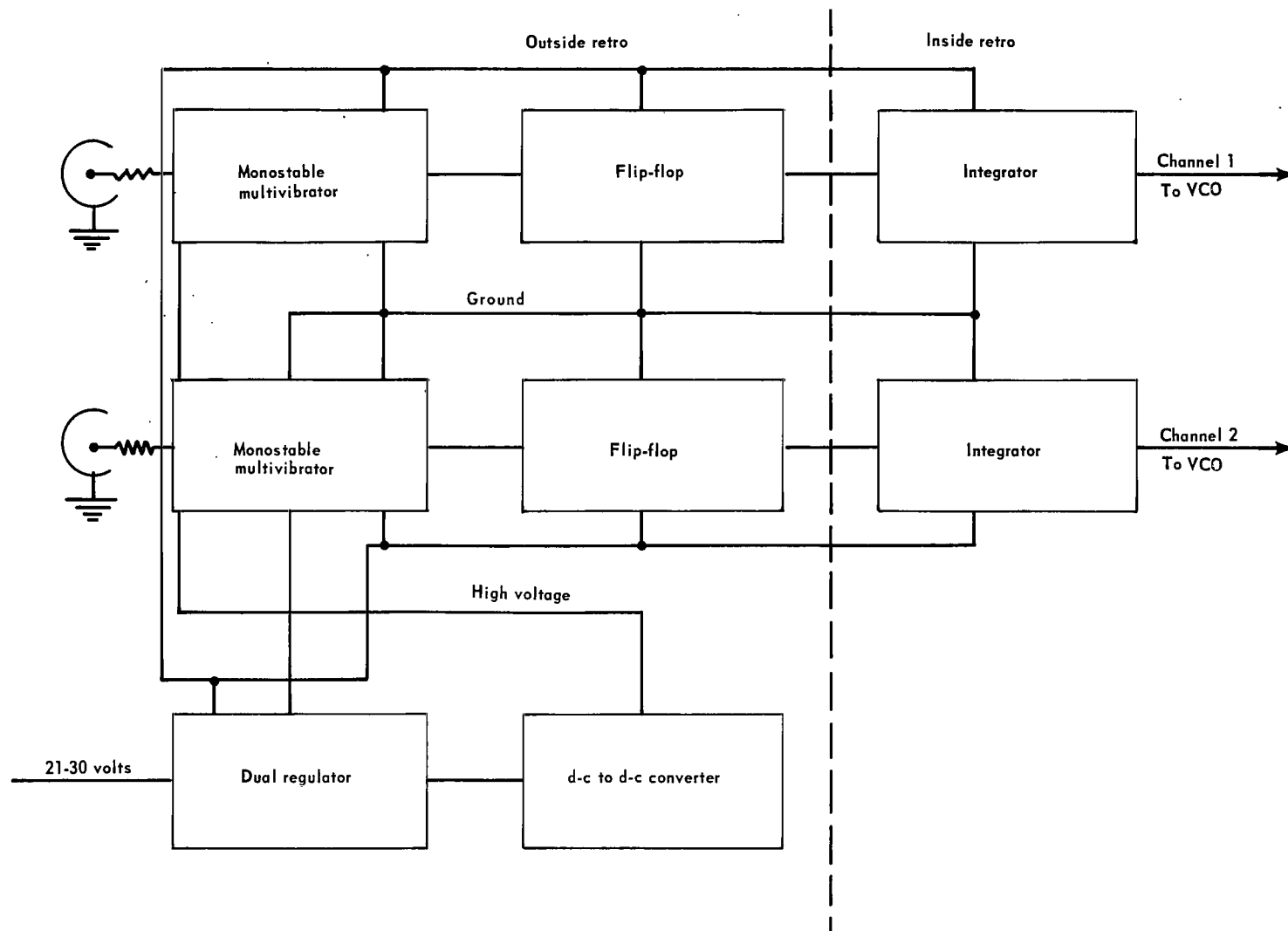


Figure 14.- Block diagram of MA-9 electron flux detector.

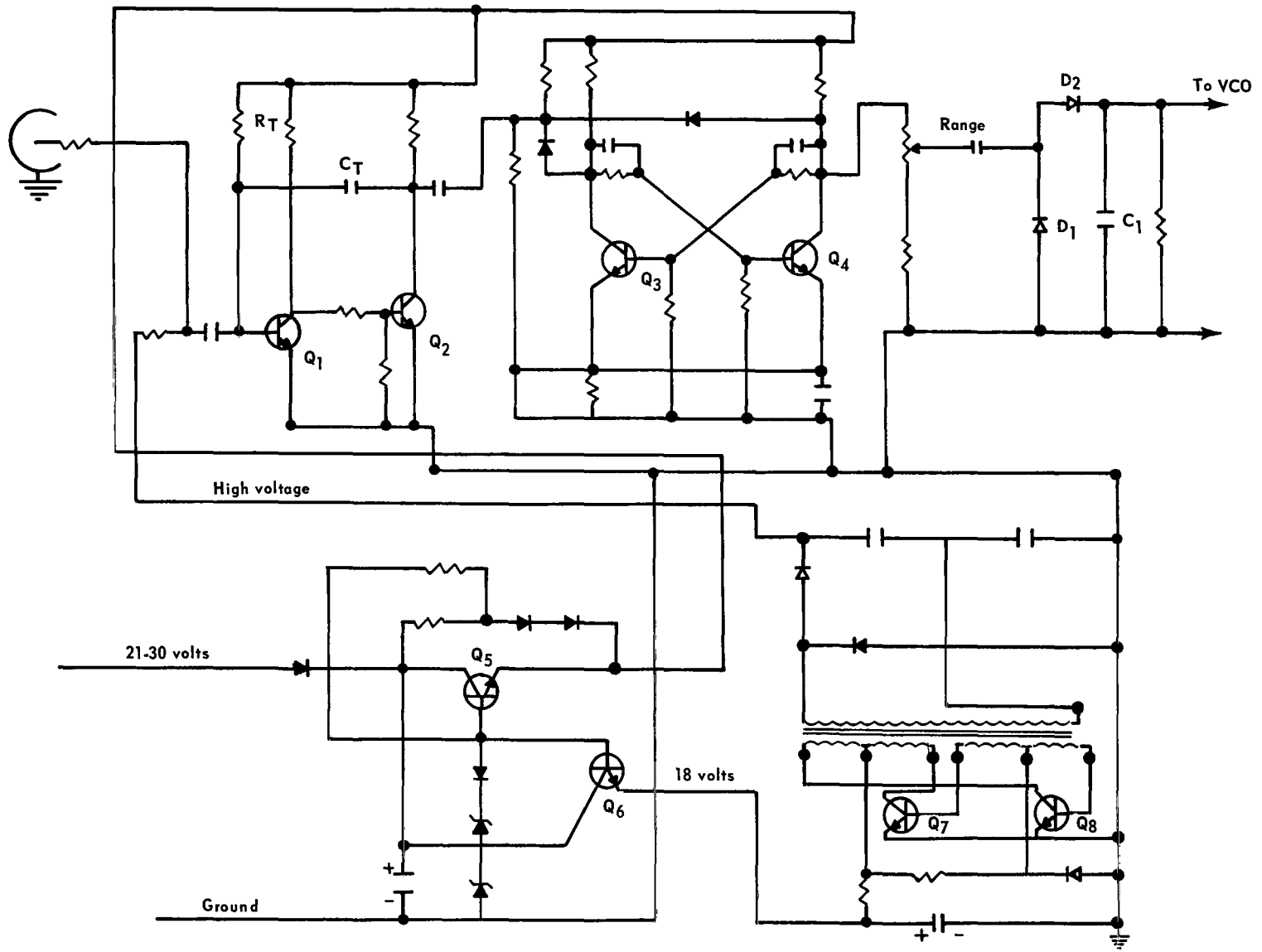


Figure 15.- Counter schematic.

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